LANGMUIR PROBE MEASUREMENTS IN PLASMA SHADOWS

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ABSTRACT. When immersing a target into a plasma streaming along magnetic field lines, a distinct shadow region extending over large distances is observed by the naked eye downstream of the target.

In this work we present an experimental study of the effect applying Langmuir probes. In contrast to expectations, there are only marginal changes in the profiles of temperature and density behind masks that cut away about 50% of the plasma cross-section. On the other hand, the mean density is drastically reduced by an order of magnitude. First attempts to simulate the observations by solving the classical 2D diffusion equation were not successful.

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1. INTRODUCTION

Preceding experiments at the PSI-2 showed shadows which were produced by objects placed into the plasma, e.g. probes. Downstream of these objects, i.e. in the direction of the flux, dark areas were formed while upstream of these objects brighter areas sometimes appeared (inverse shadows). These shadows can be observed over large distances ($\geq$ 1m) with the naked eye.

Understanding of plasma shadows in a magnetically confined plasma and their influence on the whole plasma cross-section is important for the improvement of invasive plasma diagnostics and for optimising limiters. The effect causing plasma shadows was unknown and to our knowledge has not been investigated previously. The primary goal of this work was to diagnose the shadow region with Langmuir probes. In addition, 2D diffusion based calculations were made in order to model the observations.

In a magnetically confined plasma the motion of charged particles is highly anisotropic: they can move freely along the magnetic field lines while the perpendicular motion is a gyration. The gyro radius ($r_{\mathrm{g}} = \frac{\mathrm{v}_\perp}{\omega_{\mathrm{c}}} = \frac{m}{qB}\mathrm{v}_\perp$) of a particle of mass m and charge q is determined by the perpendicular momentum of the particle $p_\perp = m\mathrm{v}_\perp$ and the magnetic field strength B.

2. EXPERIMENTAL SET-UP

PSI-2 is a linear plasma device with a stationary direct current arc discharge ($10 \ldots 1000$ A). Consisting plasma is radially confined by an axial magnetic field. It is produced in the discharge region, consisting of a heated, cylindrical, hollow LaB_6-cathode and a cylindrically-shaped Mo-anode. The experiments were performed in the target chamber (see Fig. 1) which is separated from the discharge region by a differential pumping stage. Typical parameters are: $B = 0.01 \ldots 0.1$ T, $n_{\mathrm{e}} = 10^{16} \ldots 10^{19}$ m^{-3}, $T_{\mathrm{e}} = 1 \ldots 15$ eV,

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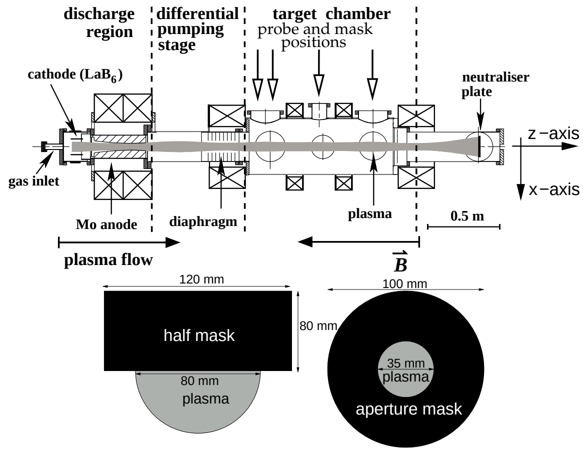

FIGURE 1. Left hand side: Plasma Generator PSI-2. Right hand side: half mask and aperture mask

$T_\mathrm{i} = \frac{1}{2} \ldots \frac{2}{3} T_\mathrm{e}$, $p_\mathrm{neutral} = 0.01 \ldots 0.1$ Pa; the plasma cross-section is about 80 mm in diameter.

Because of the hollow-shaped profile in electron temperature and density, we designed three different masks: a first cuts away the inner low temperature, low density part, a second one cuts away the outer high temperature, high density part. Finally, a third mask drastically cuts away half of the plasma. For the lack of space only the results for the two masks presented in Fig. 1 are discussed (more details are given in [1]). Because of symmetry, the circular masks should not be influenced by rotation of the plasma column [2], whereas the half mask should be affected by it. To minimize the distortion by the Langmuir probe, the dimensions of the masks were chosen to be large in comparison to the probe size.

3. EXPERIMENTAL RESULTS

The profiles of electron temperature and density were obtained by using Langmuir single probes moving vertically at positions $\Delta z = -0.064,\ 0.064,\ 0.440,\ 0.816$ m with respect to the z-position of the mask (see Fig. 1), and the origin of the x-coordinate coincides with the centre of the plasma cross-section. The Langmuir probe itself influences the plasma and a clear hollow-shaped, symmetric n_e-profile (at least expected in the undisturbed case) is not observed (see Fig. 2). In the case of electron temperature, however, the hollowness of the profile is more pronounced.

When immersing targets into the plasma the electron density typically decreases over the whole plasma cross-section. Surprisingly, the local difference between the shadowed and unshadowed region is much smaller than the global difference between disturbed and undisturbed plasma. In contrast, the electron temperature stays nearly the same. The results of the experiments are similar for both masks. The density decreases by a factor of 10 over the whole plasma column in both cases, whereas the shadowed and unshadowed region differ only by a factor of 2.

From a physical point of view the ion gyro radius should be a crucial parameter with respect to shadow formation. For this reason the experiments in argon ($r_\mathrm{g} = 2 \ldots 3$ cm) were complemented by those in helium ($r_\mathrm{g} = 0.5 \ldots 1$ cm). Some results are presented in Fig.

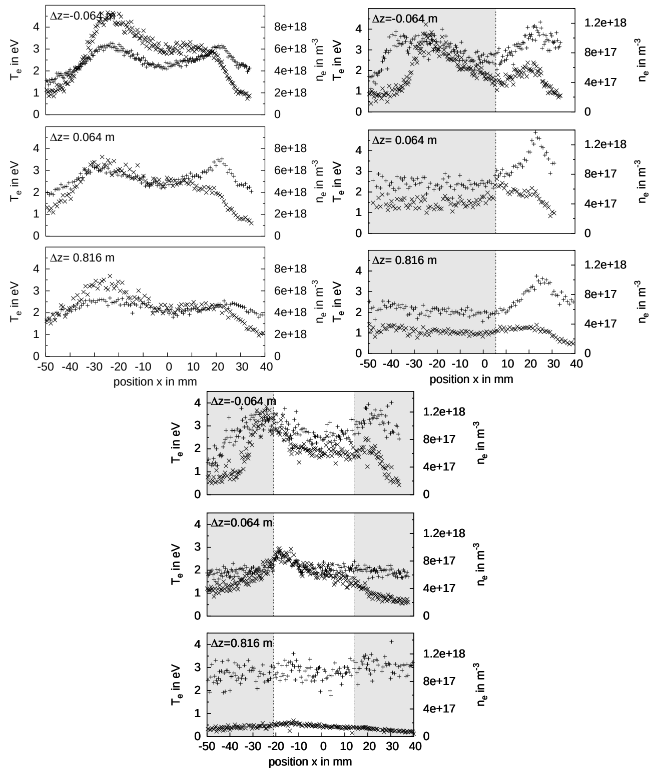

FIGURE 2. Ar-plasma (T_e +) and (n_e x). From left to right: Undisturbed, with half mask, with aperture mask. Grey areas mark shadowed regions. The centre of the plasma column is located at $x = 0$. Note the change of density scale between the undisturbed (first column) and disturbed cases (second and third column).

3. Here the profiles of the ratios ($n_{\mathrm{e,disturbed}}/n_{\mathrm{e,undisturbed}}$, $T_{\mathrm{e,disturbed}}/T_{\mathrm{e,undisturbed}}$) are plotted for argon (left) and helium (right) plasmas.

By comparing the left and right columns in Fig. 3 we conclude that the ion gyro radius is not of decisive importance as previously expected.

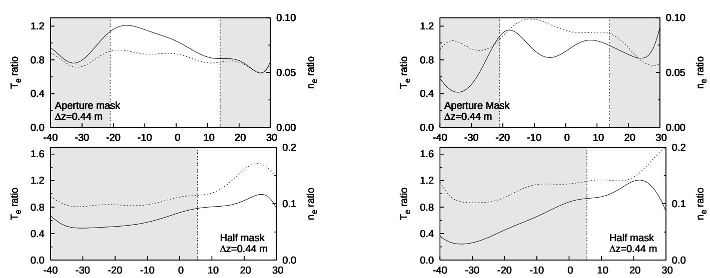

FIGURE 3. Profiles of the ratios (“disturbed”/”undisturbed”) for argon (left) and helium (right). Top aperture mask, bottom half mask. T_e dashed line and n_e solid line. Again grey areas mark shadowed regions.

4. MODELLING

Because of the rather low streaming velocity in PSI-2 (Mach numbers ~ 0.1 [3]) its influence is ignored in what follows. The particle transport is then described by a 2D diffusion equation (axis-symmetry). The set of equations reads:

$$\frac{\partial n}{\partial t} = -\nabla \cdot \vec{\Gamma} = 0 \quad \text{with } \vec{\Gamma} = -\overleftrightarrow{D} \nabla n \tag{1}$$

$$\Rightarrow 0 = \frac{1}{r}\frac{\partial}{\partial r}(r D_\perp \frac{\partial n}{\partial r}) + \frac{\partial}{\partial z}(D_\parallel \frac{\partial n}{\partial z}) \quad \text{with } z = \zeta\sqrt{\frac{D_\parallel}{D_\perp}} =: \zeta \cdot \kappa \tag{2}$$

$$\Rightarrow 0 = \frac{1}{r}\frac{\partial}{\partial r}(r \frac{\partial n}{\partial r}) + \frac{\partial^2 n}{\partial \zeta^2} \quad \text{(2D Laplace equation)} \tag{3}$$

The general solution is given in terms of $J_0(kr)$, the Bessel function of zero kind.

$$n(r, \zeta) = n_0 \frac{2a^2}{\pi} \int_0^\infty dk \Big(\frac{\sin(ka)}{(ka)^2} - \frac{\cos(ka)}{ka} \Big) \exp(-k|z|) J_0(kr), \tag{4}$$

The inner edge of the aperture mask is set to $r = a$. The boundary conditions are of a mixed type: Inside the aperture for $z = 0,\ r < a \rightarrow \frac{\partial n}{\partial r} = 0$. On the mask for $z = 0,\ r \geq a \rightarrow n = 0$. The diffusion coefficients ($D_\perp$ and $D_\parallel$) are assumed to be constant, and the plasma radius is taken as infinity. $\kappa = \sqrt{D_\parallel / D_\perp}$ is a scaling factor. The problem is analogous to a charged plane at constant potential with a central hole, a well known problem in the electrostatics [4]. For comparison with the experimental data the scaling factors were calculated using Langmuir probe measurements ($D_\parallel = \frac{1}{2}\frac{c_s^2}{\nu_\mathrm{i}} = \frac{1}{2}\frac{k_\mathrm{B}(T_\mathrm{e}+T_\mathrm{i})}{m_\mathrm{e}\nu_\mathrm{i}}$, with $\nu_\mathrm{i} = (\nu_\mathrm{ii} + \nu_\mathrm{ie} + \nu_\mathrm{in})$, $D_\perp = \frac{m_\mathrm{e}\nu_\mathrm{ei}k_\mathrm{B}(T_\mathrm{e}+T_\mathrm{i})}{e^2 B^2}$). Numbers are given in Table 1.

	Ar	**He**
$D_\parallel$ [m^{2}s^{-1}]	40	560
$D_\perp$ [m^{2}s^{-1}]	0.016	0.007
κ	50	275

TABLE 1. Diffusion coefficients calculated from probe data

In Fig. 4 the normalised densities obtained from the 2D-diffusion equation and the Langmuir probe measurements are shown. Due to the large κ-values, the decreasing of the density should be very localised in the radial direction downstream of the mask. As is to be seen from Fig. 4, the simulations fail completely to reproduce the experimental findings. The simulation takes into account only classical perpendicular and parallel diffusion with constant diffusion coefficients. This is completely insufficient. Obviously, a much higher perpendicular diffusion ($D_\perp \approx 100\frac{m^2}{s}$) is to be postulated. Alternatively, an additional perpendicular velocity, as observed at PISCES [5], may explain the observations.

5. CONCLUSIONS

- Immersing a large mask into a magnetized plasma, covering about 50% of its cross-section, the density is reduced by an order of magnitude on a global scale compared to the undisturbed plasma. At the same time the electron temperature is only marginally affected.

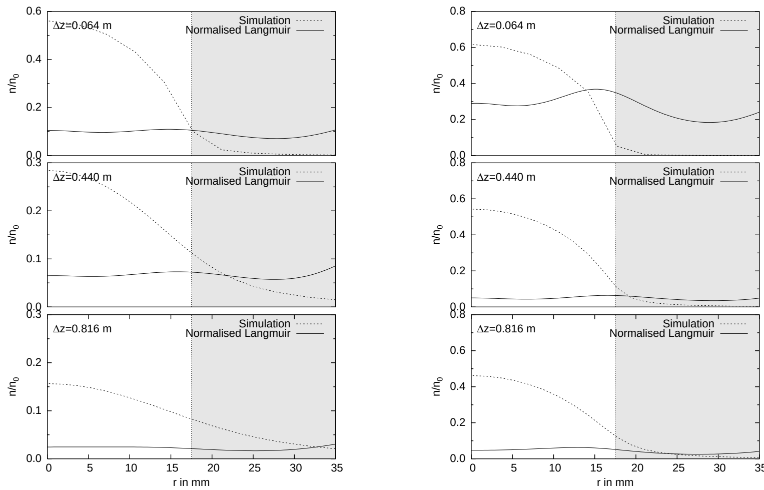

FIGURE 4. Comparison between experiment and simulation. Left Ar, right He.

- The local differences in plasma parameters (T_e, n_e) between shadowed and unshadowed regions of the plasma cross-section are rather small in contrast to the clearly visible shadows.
- A possible explanation for the visibility of the shadows is the pronounced nonlinear dependency of the emissivity on electron temperature ($\epsilon \sim n_\mathrm{e} \exp(-\frac{E_{z,i}}{k_\mathrm{B} T_\mathrm{e}})$) see e.g. [1].
- The profiles are conserved over a long distance.
- The comparison of the experiments in He and Ar did not confirm the expected importance of ion gyro radius.
- The replenishment of the shadowed region may be caused by plasma rotation. However, in case of the aperture mask experiments rotational effects can be excluded due to circular symmetry.
- A theoretical approach based on purely classical diffusion fails completely to describe the measurements. To achieve consistency a considerably enhancement of perpendicular diffusion would be needed.

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